Domain wall displacements in amorphous films and multilayers studied with a magnetic force microscope

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Domain wall displacements in amorphous films and multilayers studied with a magnetic force microscope

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The magnetic force microscope (MFM) was used to study the displacement of domain walls (DW) in amorphous TbFe alloy films and Co/Pd multilayer films with high spatial resolution. The reversible bending of domain wall segments pinned to defects and irreversible, jumplike displacement of domain wall segments were imaged with the MFM in an applied magnetic field. The maximum reversible displacement of domain walls was 50–100 nm and the length of the segments which reversibly curved in the field was about 150 nm. Measurement of the change in radius of curvature of a DW segment in response to an applied field allowed estimation of the DW energy density and self-demagnetizing field of the film acting on the DW. The DW energy density for the TbFe films was about 1 erg/cm^2. It was shown that the self-demagnetizing field acting on a domain wall depends on the domain structure surrounding the studied DW segment. For instance, for a film with saturation magnetization 100 G and thickness 80 nm, which exhibited a mazelike domain structure, the demagnetizing field varied from 100 G in the center of a mazelike domain to 400 G near the edge of a domain. The irreversible displacement of a DW was not a continuous process. The 200–400 nm long DW segments exhibited jumplike motion over distances of 100–150 nm. © *1997 American Institute of Physics.* [S0021-8979(97)38808-2]

I. INTRODUCTION

Domain wall (DW) motion in amorphous and multilayer films as well as in all other hard magnetic materials can be described in two parts: (1) the quasifree DW motion under an external magnetic field exceeding the coercive force; and (2) the viscous DW motion under an external field approaching the coercive force. The quasifree wall motion in amorphous films was experimentally studied in Refs. 1–5 and considered theoretically in terms of the Landau–Lifshitz–Gilbert equation in Refs. 6–9. In this case, the velocity of a DW exhibits a linear dependence on the external magnetic field. As the external field approaches the coercive field of the material, the dependence of the DW velocity on field becomes nonlinear.[3,10,11] The phenomenon underlying this observation affect all magnetic materials which exhibit hysteresis. The magnetization of these materials exists in metastable states which transform to stable states by a combination of field induced transitions and thermal activation. When the magnetization process is due to the displacement of domain walls, these metastable states arise from the interaction of DWs with defects or inhomogeneities in the material. Defects pin the domain walls. Thermal activation causes detachment of DWs from defects, allowing jumplike DW segments displacement to the next pinned state (next defect).[10,12–14] If the external field and temperature are insufficient for unpinning domain walls from defects, DW segments reversibly bend under the influence of the field like a membrane.

In this article we present the results of a magnetic force microscope study of reversible and irreversible displacements of domain walls in amorphous TbFe alloy films and Co/Pd multilayer films.

II. EXPERIMENT

The samples of amorphous TbFe and multilayer Co/Pd films were prepared by sputtering in an argon atmosphere. The TbFe film was deposited on a glass substrate and protected from oxidation by encapsulation with 20-nm-thick SiN layers. The Tb content in the film was 18 at. % and the film thickness was 80 nm. The Co/Pd multilayer film consisting of 10 pairs of Co and Pd layers of individual thickness of about 1.5 and 6.5 Å, respectively, was deposited on a Si(111) substrate. Both films exhibited perpendicular magnetic anisotropy, i.e., the magnetization was perpendicular to the film surface.

For this study a Nanoscope III Multimode™ magnetic force/atomic force microscope (Digital Instruments, Santa Barbara, CA) was used. The microscope was operated in the ''tapping/lift'' scanning mode which combines constant interaction and constant height modes to separate topographic and magnetic signals.[15,16] Magnetic force gradient images were obtained by detecting MFM tip oscillation amplitude in constant height mode. The scanned probes were batch fabricated Si cantilevers with pyramidal tips coated with a CoCr film alloy.[17] All MFM data shown in this article were collected with the tip magnetized approximately perpendicular to the sample surface (*z* direction), making the MFM mostly sensitive to the second derivative of the *z* component of sample stray field. All MFM images presented in this article were obtained with tip-sample separation of 30–50 nm and tip oscillation amplitude of 20–30 nm. The drive frequency of cantilever was chosen above the resonance frequency of the cantilever near the point of maximum gradient of the cantilever resonance curve.

A magnetic field perpendicular to the sample surface was applied *in situ* using Helmholtz coils around the MFM. It is necessary to mention that while imaging with the MFM, the sample is also exposed to the local magnetic field of the MFM tip. This field is a few hundred Oe at the surface of the tip, but it decreases sharply with distance from the tip.[18] At a distance of 50 nm from the tip which corresponds to the

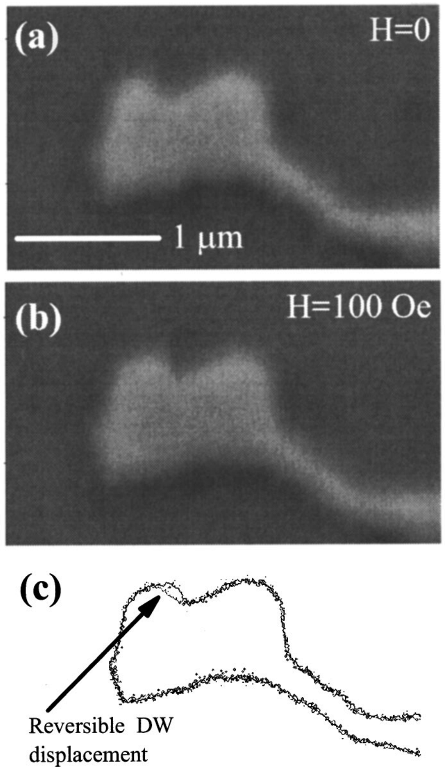

FIG. 1. MFM images of a domain in a Co/Pd multilayer film illustrating the reversible displacement of a DW segment: (a) image of the domain in zero external field, (b) image of the same domain in an external field of 100 Oe, (c) contours of the domains in the images shown in (a) and (b). The MFM tip field, the external field and the magnetization in the ''white'' domain are in the same direction.

average ''lift'' mode tip sample separation used in this study, the field is about 30 Oe.

III. RESULTS AND DISCUSSION

Reversible displacements of DW segments were observed under the application of an external magnetic field. MFM images of domains in a Co/Pd multilayer and an amorphous TbFe films in zero field and in an external field are shown in Figs. 1(a), 1(b) and 2(a), 2(b), respectively. The positions of DWs in the images were determined by making domain contours at a certain level of gray-scale corresponding to a certain MFM response between the ''black'' and ''white'' domain levels using image processing software. The contours of the domains in the Co/Pd film under the field $H=100$ Oe and zero field are shown in the Fig. 1(c). Figure 2(c) shows the domain contour for the zero field image of the TbFe film on top of the image of the same domain in an applied field of 200 Oe. When the external field was returned to zero, the DW moved back to its initial position. As seen in the figures, the DW segments bent in the external field. The maximum reversible displacements of DW segments observed in this study were 50–100 nm and the lengths of segments which reversibly curved were about 150 nm. The equilibrium radius of curvature R of a DW segment pinned to two defects is determined by the following relationship:

$$\sigma_w/R=2M_2(H+H_d+H_{\mathrm{tip}}), \tag{1}$$

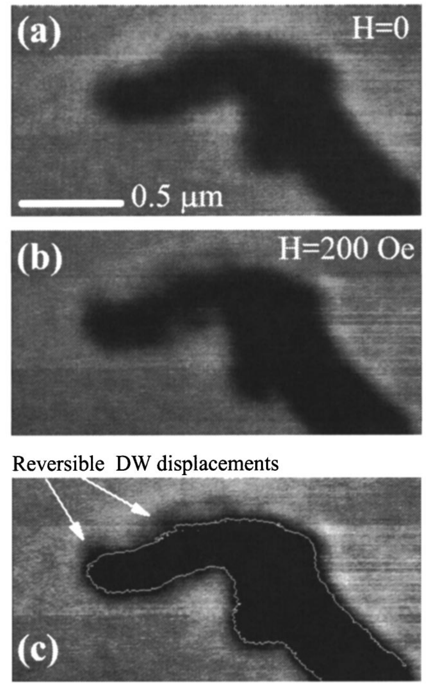

FIG. 2. MFM images of a domain in an 80-nm-thick $Tb_{18}Fe_{82}$ amorphous film illustrating reversible displacements of the DW segments: (a) image of the domain in zero external field, (b) image of the same domain in an external field of 200 Oe, (c) contour of the domain in the image shown in (a) overlayed on image (b). The MFM tip field is opposite the external field and the magnetization in the ''black'' domain.

where σ_w is the DW energy density, M_s is the film saturation magnetization, and H, H_d, and H_{tip} are the external field, self-demagnetizing field, and field from the MFM tip, respectively. Using (1) and measurement of radii, R_1 and R_2, of DW segments under two different external fields, H_1, and H_2, the domain wall energy density and self-demagnetizing field acting on the DW were estimated. The DW energy density for the TbFe film was about 1 erg/cm^2 which is close to

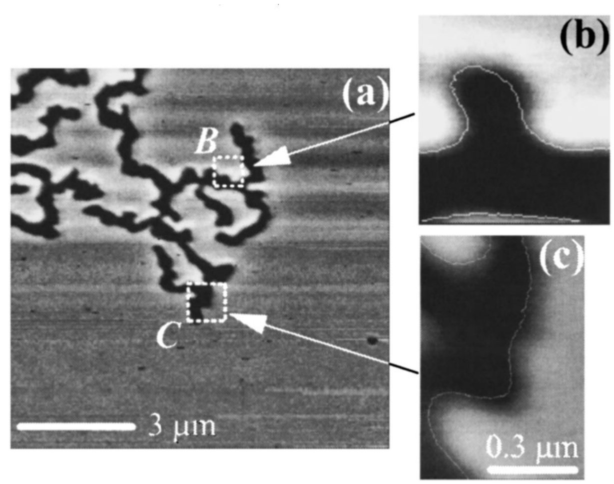

FIG. 3. (a) MFM image of a mazelike domain in an 80-nm-thick $Tb_{18}Fe_{82}$ amorphous film. (b), (c) High resolution MFM images of the domain in an external field of 200 Oe in areas B and C outlined in (a). The white lines indicate the DW contour in zero external field. The MFM tip field is opposite the external field and the magnetization in the ''black'' domain.

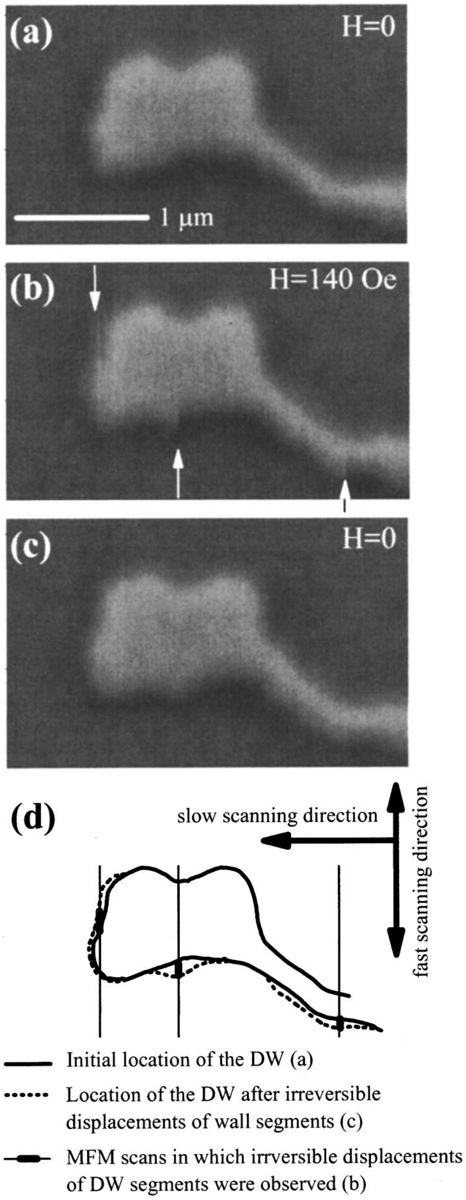

FIG. 4. MFM images of a domain in a Co/Pd multilayer film illustrating the irreversible displacement of the DW segments: (a) initial state of the domain in zero external field, (b) image obtained under the field of 140 Oe. The arrows show the MFM scans in which the irreversible ''jumps'' of DW segments were observed. (c) Final state of the domain after decreasing the external field back to zero. (d) Smoothened contours of the domains shown in (a) and (c). The fast and slow scanning directions are shown with the arrows in the corner. The MFM scans where the irreversible ''jumps'' of the DW were observed in (b) are also indicated. The MFM tip field, the external field and the magnetization in the ''white'' domain are in the same direction.

the theoretical value.[19] The self-demagnetizing field depended on the domain structure surrounding the studied DW segment. For instance, for the TbFe film with saturation magnetization 100 G and thickness 80 nm which exhibited a mazelike domain structure [Fig. 3(a)], the demagnetizing field in the area C [Figs. 3(a), 3(c)] located at the edge of the mazelike structure is about 400 Oe; whereas the demagnetizing field in the area B [Figs. 3(a), 3(b)] located closer to the center of the mazelike domain than area C is about 200 Oe. In the case of reversible DW displacements the MFM images show the location of DW in ''lift'' mode. Thus, in estimating the demagnetizing fields, the field of the MFM tip at a distance equal to the ''lift'' height from the tip was taken into account. For a ''lift'' height of 50 nm, the tip field was about 30 Oe[18] and, in this case, it was opposite the external field.

Irreversible displacements of DW segments were also observed in imaging the domains with the MFM in an external field. Figure 4 shows a series of three images of the same domain in the Co/Pd film: (a) the initial state in zero applied field, (b) the image obtained in a field of 140 Oe, and (c) the final state after decreasing the external field back to zero. Smoothened contours of the domain are shown in Fig. 4(d). It can be seen in the figure that while imaging the domain in an external field, some segments of the DW displace in a jumplike fashion [Fig. 4(b)], and the final location of the DW is different from the initial location [Fig. 4(d)]. All irreversible displacements of the DW were observed to consist of individual ''jumps'' of 200–400 nm long segments of the DW over distances of 100–150 nm. Most likely the irreversible ''jumps'' of DW segments occurred while scanning in ''tapping'' mode when the tip field acting on the sample is high. Thus, the actual field that caused the ''jumps'' of DW segments shown in Fig. 4 is the sum of the external field and the tip field which is about 300–400 Oe at a distance of 5–10 nm from the tip.[18]

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